DIASTROPHISM AND THE FORMATIVE PROCESSES. VIII

THE QUANTITATIVE ELEMENT IN CIRCUM-CONTINENTAL GROWTH

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In a previous article of this series (VI, p. 271) we endeavored to show that the depth of the ocean does not, in itself, set limits to the thickness of the strata laid down in it—when these are measured in the usual way—though it does determine the amount of material required to build the continental terraces oceanward to given distances and thus indirectly affects the thickness of strata actually attained by a given amount of material. As a quantitative factor, then, ocean depth has its importance in determining the amount of peripheral growth that may arise from a given amount of sediment; or, if the peripheral growth be given, the amount of sediment required to accomplish it and, by interpretation, the time. The unit of such quantitative measurement is found in terms of radial extension rather than stratigraphic thickness. This distinction of terms and methods arises from the fact that the ocean depth affects the *area* of each stratum because of its inclined attitude. The quantity of sediment in the circum-continental terraces is one of the elements by which the denudation of tributary land is measured; or, the rate of denudation being roughly known or assumed, the amount of sediment in the terraces is a measure of the time occupied in the formation of the terraces. It thus becomes not only an index of the antiquity of the terraces but gives some incidental testimony as to their history.

In such rough approximations as alone are possible in studies of secular denudation and accumulation, we may assume that the surface movements of the ocean waters were effective in the same way and to the same extent in all ages, though this assumption was

probably not strictly true and perhaps not approximately true in some cases. On this assumption the topset deposits of the continental shelves were of the same order of vertical depth as those recently formed. These we commonly agree to limit to the work of the upper 100 fathoms of water, though the sum of the thicknesses of the topset *strata* is not limited to 100 fathoms. The variable effects due to variable ocean depths are hence manifested almost solely in the foreset beds formed on the terrace faces overlooking the abysmal deeps.

Now if we assume, for a concrete example, that the slope of these foreset beds is 1 in 12, and that the mean depth of the abysmal part of the ocean adjoining is 5,000 meters, a symmetrical stratum of such an order as to advance the terrace horizontally one meter oceanward will be 1/12 meter thick, and will have a radial width of 60 kilometers. This stratum is equivalent to a vertical stratum one meter wide and 5,000 meters deep. If any other slope than 1 to 12 be taken as representative, a similar result follows; that is, a stratum that measures one meter horizontally at the surface, may be reduced to a vertical stratum one meter wide and 5,000 meters deep. The measure of *horizontal* advance and the measure of ocean depth thus appear to be the true factors in measuring sedimentary growth about the continents and to be conveniently simple in use. The *slopes* and the *stratigraphic* thicknesses may in many cases be neglected. They must of course be duly taken into account in their own appropriate fields but these are not precisely this field.

Notwithstanding the simplicity of the method thus deduced, all determinations of the quantitative values of the sediments of the circum-continental terraces are embarrassed by several serious difficulties. In spite of these, however, some working concepts may be formed that have value, even though they do not rise above very rough approximations.

In any specific attempt to deal with the sediments of the terrace shelf it is of course necessary to select the epoch or the formation from which the beginning of terrace growth is to be reckoned. It is idle in the present state of knowledge to go back of the Cambrian period and in many problems a much later date is best taken as the starting-point.

When this datum point is chosen there arise at once special difficulties in determining what were the landward and bottom boundaries at the start, for even the landward edge at the surface is largely concealed by later deposits, or has been cut away, while its lower parts and the bottom are generally inaccessible except as diastrophism has forced them into view. In few cases—probably in no case—has a terrace shelf throughout its history been built oceanward solely. In most cases the sea has advanced upon the land and the topset deposits have crept out upon the continent as well as oceanward. The landward advance has in many cases been interrupted by diastrophic movements and the shore line forced seaward, sometimes even beyond the initial line. Later a new advance has taken place from this line of retreat and so the oscillation has gone on. As a result of this the innermost edge of sedimentary deposits is liable to lie farther landward than the line from which growth began at the opening of the epoch chosen. The border sediments that thus lap upon the continent—defined as it stood at the outset—must of course be taken into account but not as extensions of the continent; they are rather superficial replacements or over-placements and, so far as determinable, are usually limited in depth and relatively small in quantitative value.

When pre-Paleozoic formations come out to the present coastline the location of the inner border of the terrace formed after the initial epoch is little better than conjectural. Some suggestions of value may spring from the trend of the border line in adjacent regions and from the consistency of value of any assigned configuration.

Probably the best approximation to the initial line of growth may be reached by setting aside for compensation purposes all sediments that are known to lap upon the continent as it stood at the outset, while such border sediments as are known to be deep and to show no signs of overlap are regarded as belonging to the continental outgrowth. In this it is assumed that any overestimates in the volume of the basal parts will be made good by the sediments of the overlap set aside for this purpose. It will be shown presently why the basal parts are not as likely to lead to overestimates as their apparent uncertainty may lead one to think. They are not wholly uncertain.

Where notable folding or faulting has taken place—and this is common near the coasts—it may be possible to determine more directly how far landward thicknesses of sediment of the order of the ocean depth have once extended, for the upturned beds may reveal them. Such observations must, however, usually give only a minimum extension; the evidences of the maximum extension have usually been cut away by erosion. An additional minimizing effect usually arises from the compression and distortion of the sediments under diastrophic thrusts. Their observed horizontal breadth may be much short of their original depositional breadth.

Students of terrestrial dynamics of all schools will probably agree that the borders of the continents have been the seats of exceptional folding and faulting. Observation and most theories, however diverse otherwise, lend support to this view. It is probably safe, and even ultra-conservative, to take the innermost line of continuous, thick, folded sediments as the landward border of the outward-built terrace, if, of course, these sediments are later than the time fixed upon as the beginning of the terrace-building epoch.

As already remarked, it is useless at present to consider circum-continental terraces older than the Paleozoic, for the metamorphisms and distortions of the earlier terranes and their wide concealment forbid their treatment in any satisfactory way. None the less, there is no good ground to doubt that the oceanward borders of the Proterozoic lands were affected for long periods by the process of terrace-building. The clastics form a notable factor in the Proterozoic terranes; they form a factor, though a less notable one, of the Archean also, and, under the planetesimal view, of terranes below the visible Archean. Whatever, therefore, may have been the original oceanward slopes of the submerged borders of the continental nuclei during the very earliest eras, normal topset and foreset slopes encircling these should have been acquired during the progress of the Proterozoic era. Except, therefore, as modified by diastrophism late in Proterozoic time or at its close, the oceanward face of the continental masses should have borne the normal sedimentary configurations.

Regarding the effects of diastrophism, I think it will be agreed quite generally that the mean results of long stretches of time tend

rather to steepen the seaward gradients of the coasts than to flatten them; tend rather also to deepen the adjacent ocean than to shallow it. Theoretically this would seem quite certainly true if any tenable form of isostasy is effectual in diastrophism, and of this there seems less ground for doubt as inquiry goes on. On the observational side, the frequency of fore-deeps and of notable depressions off the continental edge not definitely shaped as fore-deeps seems to support this. It may be assumed, therefore, with much probability, that from Cambrian time onward topset and foreset action kept rebuilding the form of the circum-continental terraces into slopes that lay within their own normal range of variation—diastrophism aside—and that the mean ocean depth bordering the continents was not less than the normal mean depth. It may further be assumed with high probability that the mean effect of diastrophism, when it intervened, was to increase the border slope and the border depth, while it compacted, folded, and shortened the previous terrace outgrowth.

It appears, therefore, that if the upper edge of the landward border of the oceanic basin can be fixed approximately at the epoch from which the terrace growth is to be estimated, the slope of the terrace front and the depth of the adjacent ocean may be assumed to be of the present order, with some likelihood that this assumption is in reality conservative. These considerations relieve very appreciably the embarrassments that would otherwise affect the lower and landward configurations of the circum-continental terraces when we attempt to restore them, by interpretation, for any particular post-Proterozoic epoch.

The surface area of the present continental shelf between the shore line and the 100-fathom line is usually taken at 10,000,000 square miles, following Murray. The additions to be made to this to give the full area of the built terrace when its true border lies on the landward side of the present shore line, and the subtractions that are to be made when it lies on the seaward side, can only be roughly guessed at until the geological determinations of the coastal terranes of the several continents have reached a more advanced state, for any close estimate requires data not now available. None the less, it is worth while to make rough guesses of their values on

such data as we have, if only to see what would be their meaning if the facts were as they are guessed to be. Without any pretention to accuracy, permit me to assume, on the basis of rough inspections, that for the total post-Proterozoic outgrowth the landward additions to be made to the present shelf are of the order of 40 per cent of its area, and that the subtractions are of the order of 20 per cent. My real judgment inclines to make the former more nearly 50 per cent and the latter more nearly 10 per cent; but, proceeding on what seems to me a conservative assumption, the total area of outgrowth of the post-Proterozoic circum-continental terrace, neglecting the crumpling, compacting, and shortening that have arisen at times from lateral thrusts, amounts to 12,000,000 square miles.

The coast line of the present continent is sometimes taken as 125,000 miles. For our present purposes a measurement on less curved lines such as to represent the middle of the shelf belt encircling the continents is more suitable, and an estimate on this basis gives about 100,000 miles. The mean breadth of the constructive terrace will then stand at 120 miles. Checked by direct measurements in some of the best determined representative cases this seems conservative.

Let us now turn to the sources of sedimentary supply. It would lead to large errors if each unit of the sea border were assumed to be fed with sediment from the whole area of a strip of land abutting on it and reaching back to the heart of the continent, for in the first place, much of the drainage runs away from the coast, and, in the second place, there is more or less coastwise drift that denudes some tracts and builds out others disproportionately. These factors have no doubt varied from age to age, and perhaps varied greatly, but our immediate purpose is to secure a rough concept of processes as they now are and as they are related to the present accumulation of sediments. These may be qualified later to fit the mean secular conditions or the specific conditions of any particular problem.

At present the continental surfaces may be divided into three classes in respect to the transportation and lodgment of sediments: (1) transportation into interior undrained basins which contribute nothing immediately to circum-continental growth; (2) trans-

portation toward the continental interiors, with a possibility or probability that more or less of the sediment will at length reach the coast by a long and circuitous route but with a liability also of lodgment in lake basins, on low plains, in estuaries, embayments, gulfs, or other dependencies of the ocean, in consequence of which the sediments are consumed in building up depressions in the interiors of continents rather than building out their borders; and (3) direct transportation to the ocean down the border slopes of the continents; or in briefer terms: (1) internal drainage with no oceanic connection, (2) internal drainage with indirect oceanic connection, and (3) direct oceanic drainage. Murray places the area of the first class at 11.5 million square miles out of a total of 55.7 million, or a little more than 20 per cent. Leaving out the circum-polar region that cannot now be treated, there remain about 40 million square miles to be placed under classes two and three. I know of no authoritative division of this area between these classes, nor do I see how any but a somewhat arbitrary division can be made, for the two classes grade into one another in a very intricate way. If we put into class three only the drainage from the coastward sides of the mountains and other elevated tracts that so generally border the continents and add the drainage from the coastal flats where elevations are absent, the resulting area will be inferior to that of the great interior basins. So likewise if, for another line of approach, we turn to the geological record, as now known, the amount of clastic sediments embraced in the coastal slopes seems much inferior to that which is embraced in the great interior terranes. But, as a portion of the sediment that goes inward at first, later reaches the exterior of the continent, let the 40 million square miles be divided equally between the class which contributes to building up the interior and the class that contributes to building the continents outward. We have already taken the length of the circum-continental shelf belt as 100,000 miles. The assigned 20 million square miles tributary to it gives a working mean of 200 square miles tributary to every mile of length of the shelf.

Much study has been given to the determination of the average rate of denudation of land surfaces under present conditions in the

endeavor to establish a mean rate serviceable for computing the age of the earth. The more recent representative treatments dealing with specific data may be found in the papers of Walcott,[1] Sollas,[2] Dole and Stabler,[3] Joly,[4] Becker,[5] Clarke,[6] Arthur Holmes,[7] in which may also be found references to earlier studies. The data of the United States Geological Survey, as organized and tabulated by Dole and Stabler, and discussed by Clarke, furnish the most definite and best determined material available, as well as that most suited to our purpose. It is not the rate of the complete denudation of the land which we wish to use in this discussion but only that part of it which found lodgment on the continental terraces. This embraced chiefly materials of certain degrees of coarseness or gravity and a certain portion of the dissolved material.

Clarke has pointed out the wide differences in the data obtained from different regions and has assigned reasons for these. It appears in particular that the average denudation of the basins of the Amazon and Uruguay rivers is but a trifle over one-half that of the Mississippi and St. Lawrence basins, though the precipitation on the tropical basins is nearly double that on the temperate basins. The difference is assigned to the forest clothing of the tropical basins. It appears from such data as Clarke found available that the mean denudation of the river basins of Europe is 100 tons per square mile, of Asia 84 tons, of North America 79 tons, of South

[1] C. D. Walcott, "Geologic Time, as Indicated by the Sedimentary Rocks of North America," *Jour. Geol.*, I (1893), 639–76.

[2] Sollas, Brit. Assoc. Rept., Address to Sect. C, 1900, quoted by Joly in *Radioactivity and Geology* (1909), p. 246; Presidential Address, *Quar. Jour. Geol. Soc.*, May, 1909.

[3] R. B. Dole and H. Stabler, "Denudation," *U.S. Water Supply Paper 234* (1909), pp. 78–93.

[4] J. Joly, *Radioactivity and Geology* (1909), chap. xi; *Phil. Mag.*, 6th ser., XXII (1911), 358; *Trans. R. S. Dublin*, VII (1899), 23.

[5] George F. Becker, "The Age of the Earth," *Smith. Misc. Coll.*, LVI, No. 6 (1910). "Halley on the Age of the Ocean," *Science*, N.S., XXXI (1910), No. 795, pp. 459–61.

[6] F. W. Clarke, "A Preliminary Study of Chemical Denudation," *Smith Misc. Coll.*, LVI, No. 5 (1910); "The Data of Geochemistry," *U.S. Geol. Surv. Bull. 491*. 2d ed. (1911), p. 60 f., 137–42, 466–67.

[7] Arthur Holmes, *The Age of the Earth* (1913), chaps. iv–vi.

America 50 tons, and of Africa 44 tons.[1] Of course the data for Africa, South America, and Asia are particularly imperfect, but probably the general import of the figures is essentially true. We may push the essence of Clarke's interpretation a step farther and point to the general correspondence of these figures with the degrees of surface cultivation that obtain in these continents. These stand in essentially the same order, viz., Europe, Asia, North America, South America, and Africa. Of course other factors than soil cultivation enter into the results, but it is obvious that a much cultivated surface, softened by soil-tilth and left naked in its softened state for at least a portion of the year and perhaps for all the year, will suffer much more rapid denudation, other things being equal, than surfaces that are constantly mantled with vegetation and whose soils are knit into coherence by a mat of roots. The distinction between the resistance to denudation of native surfaces in humid areas under temperate and tropical conditions, on the one hand, and well-cultivated surfaces, on the other, seems to find peculiar exemplification in the data of Dole and Stabler—the best now available from which to draw tentative generalizations for working purposes. The measurements on which their results are based have been made in very recent years, in the main, and represent the rate of denudation incident to the present state of surface culture. Soil wastage is now notably high. The raising of corn, tobacco, cotton, and potatoes is peculiarly tributary to the leaching and wash of soils. In a somewhat different way, roads are also specially tributary to wash. In very marked contrast to the present state of the surface was its condition just previous to settlement by the whites. The soil of the forested regions was not only protected by a permanent overgrowth of trees and a tangled undergrowth of bushes and herbaceous plants and by a mat of leaves, twigs, and fallen timber, but by a network of roots and rootlets which bound the soil together. The flow of surface drainage was delayed and equalized by the one group of agencies while the soil was rendered resistant to the relatively gentle water action thus insured by the other. On the prairies, the dense mat of native

[1] F. W. Clarke, "A Preliminary Study of Chemical Denudation," *Smith Misc. Coll.*, LVI, No. 5, (1910), p. 7.

grass was abetted by an even denser mat of root fibers to which it adhered tenaciously at its base, and these together made the native sod peculiarly resistant to erosion. In the ravines and meadows the rank "slew" grass, attached even more tenaciously to a tough mass of fibrous roots, was an especially effective defense against the action of floods and freshets where they were liable to do their most effective work. In those early days, as I distinctly remember, the ravines and upland valleys in times of freshets usually ran clear save that their waters were amber-tinged from vegetal extract. The banks of the brooks were then not only close-sodded to the very water's edge, but by their gradual growth closed in on the narrow, pellucid stream between them. The same brooks now, under close pasturage and the feebler turfing of the exotic grasses that have replaced the native sod, have cut open ditches, several times as wide and these are being further widened anually. Under the native conditions even the floods of spring time were but slightly turbid, whereas now the flush of every shower runs black with sediment. Comparing earlier and later impressions of identical areas in the Mississippi Valley, where cultivation has followed native conditions, whether of forest, plain, or meadow, the rate of denudation under culture seems clearly to be some appreciable multiple of the earlier rate, perhaps a very notable multiple. The matter should be determined by direct trials where either the conditions are under complete control or the data for comparing areas not under control are complete and well in hand.

The statistics of Dole and Stabler[1] give for the surface denudation of the United States taken as a whole a mean rate of 1 foot in 9,120 years. For our purpose it is important to know whether this and other large averages are suited for use in the study of circum-continental shelves when these are dependent for their growth chiefly on sediment brought from the drainage slopes of the sea borders. It might seem a natural inference that the coastal slopes should receive a larger rainfall, in general, than the average surface of the continent and so perhaps be denuded more rapidly. But rainfall commonly increases the vegetal clothing and this tends

[1] *Water Supply and Irrigation Papers 231–236*, "Denudation," p. 83.

the other way. To see whether the rates of denudation of the coastal border tracts are essentially the same or essentially different from those of the general continental surfaces, the rates given by Dole and Stabler for the districts of the North Atlantic (1 foot in 13,200 years), the South Atlantic (1 foot in 8,520 years), the North Pacific (1 foot in 19,200 years), and the South Pacific (1 foot in 9,320 years), including in each case only the area within the United States, were combined and compared. The rates, averaged without weighting, were found to give a common rate of 1 foot in 12,180 years. If the Laurentian basin (1 foot in 19,320 years) is reckoned in, the unweighted mean rate rises to 1 foot in 13,476 years. If the Colorado River basin (1 foot in 5,280 years) is also reckoned in, the mean falls back to 1 foot in 12,110 years.

The data for some of the sub-districts are very suggestive. For example, the basins of the Penobscot (1 foot in 24,000 years), the Kennebec (1 foot in 25,200 years); the Androscoggin (1 foot in 21,600 years), the Presumpscot (1 foot in 25,200 years), the Saco (1 foot in 25,200 years), the Merrimac (1 foot in 32,400 years), and the Connecticut (1 foot in 24,000 years) are averaged without weighting, the mean rate is 1 foot in 25,371 years. These notably low rates are probably due in part to the numerous catchment basins on the morainic surfaces of these New England basins, but in no small part also are they probably due to the fact that large portions of New England once under plow have been permitted in recent years to return to a wooded or grassy state. It is of interest to note here that the drainage area of Lake Superior, so far as it lies in the United States, which has only been brought partially under culture, has a denudation rate of 1 foot in 37,200 years.

The erosion of the South Atlantic district (1 foot in 8,520 years) is $2\frac{3}{5}$ times as fast as that of the North Atlantic district (1 foot in 13,200 years), though the gradient of the former is below rather than above that of the latter. Of like import is the erosion rate of the North Pacific slope (1 foot in 19,200 years) when compared with that of the South Pacific slope (1 foot in 9,320 years) more than twice as fast, though the rainfall of the former is much the higher and its gradients certainly not less steep. One of the most vital factors, probably the most vital factor, in these strong

contrasts is with little doubt the different degrees of protection afforded by their vegetal mantles.

It appears then that a review of the best data that we have relative to the present rate of denudation of the coastal slopes gives a mean rate of about 1 foot in 12,000 years. It is to be noted that this embraces tracts that reach to the border of the 30° belt where humidity is low, as well as tracts in the fairly humid mid-latitudes, and that the denudation rate of the latter is scarcely a half of that of the former in spite of the theoretical presumption that denudation should rise and fall with the precipitation. The fact that the efficiency of the vegetal mantle as a protection against erosion also rises and falls with precipitation seems to much more than offset the direct effects of increased drainage flow.

Returning to the broader question, it appears that the best available data relative to the rate of denudation on American coastal slopes at present gives a mean rate of 1 foot in 12,000 years. This is but half the higher rate usually employed in the past, based on the rate for the Mississippi Valley as a whole, 1 foot in 6,000 years. The rate 1 foot in 12,000 years still needs to be corrected for (1) the effect of the present conditions in accelerating denudation, (2) the portions of the sediments lost to the abysmal basins, (3) the portions of the solutions that are held permanently in the oceans as part of the saline element of sea water, and (4) the portions of the solutions that are precipitated to the ocean depths as the hard parts of pelagic animals and plants.

But to curtail this discussion, let us leave these corrections in abeyance and proceed on the basis of the present denudation rate, keeping in mind that it must be corrected to give true results.

Recalling that we had previously fixed upon a belt 200 miles in width as representative of the area directly tributary to the shelf, upon 100,000 miles as its length, and upon 120 miles as the mean width of the shelf, and using the denudation rate 1 foot in 12,000 years, without correction, the formation of the post-Proterozoic terrace would take approximately 108,000,000 years. This is of about the same order of magnitude as the periods usually reached for post-Proterozoic time by employing data based on general denudation in which the present rate is taken as the secular

rate. While our results must be corrected for the difference between present rates of denudation and the mean secular rate—and this correction is quite certainly large, involving other factors than the cultural one—comparisons with other modes of attack must be made previous to such corrections if these have not similarly entered into the results of these other studies.

This general concurrence in results seems to imply that the continents have made peripheral growths of the same order as their other forms of growth. This in turn implies that the continental borders have had a permanency and stability of the same order as the continents themselves.